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Bioenergy production in Central America: Integration of sweet sorghum into sugar mills

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ABSTRACT

This paper aims to evaluate the potential for electricity and ethanol production in Central America using sweet sorghum as an energy crop. Three scenarios were built to analyse sweet sorghum production in terms of the land where it can be cultivated: cropland, sugarcane land in fallow and land in continuous production (intercropping system). The land under permanent crops was not considered for this evaluation. We propose the integration of sweet sorghum into Central American sugar mills, by using the existing machinery to process it. The short growing period of sweet sorghum would allow the Combined Heat and Power (CHP) plants and distilleries to operate outside the sugarcane crushing season using sorghum bagasse and molasses as raw materials. This production could be performed 1 month before, and 1 month after the sugarcane season.

Results indicate that by growing sweet sorghum on 5% of Central America's cropland, sorghum could supply around 10% of region's electricity demand. Thus, Central America could increase its CHP share of electricity supply from 4.4% to 5.6%. The increase in renewable electricity production would allow countries such as Guatemala, Honduras and Nicaragua to reduce fossil fuel bills by USD$ 13, 10 and 20 million, respectively.

The ethanol produced from sweet sorghum during off-season can help to implement and maintain a sustainable ethanol program in the region that does not only depend on sugarcane. Sweet sorghum would allow distilleries to easily supply the ethanol required to implement an E5 or ED3 program. Central America could produce about 387 million liters of ethanol by growing sweet sorghum on 5% of its cropland. This ethanol production would help the region to reduce fossil fuel bills by USD$ 517 million by using ethanol–gasoline blends or USD$ 463 million by using ethanol–diesel blends.

Contents

1. Introduction

Fossil fuels provide about 35% of the total electricity supply in Central America, where about 78% of this energy comes from diesel and fuel oil generators [1]. This dependence on fossil fuels leaves the region in a vulnerable position in front of the rise of fuel prices and

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supply shocks. So far, biomass resources (sugarcane bagasse) provide about 4% of the total energy supply through CHP plants [2]. Currently in Central America, the main crop used to produce sugar, ethanol, process heat and power is sugarcane. The main advantages of sugarcane in relation to starchy feedstocks are that cane has fewer process stages and less energy requirements, which allow savings between 20 and 60% [3]. Nevertheless, sugarcane requires a long growing season and it can only be harvested once a year. Thus, limiting the production areas and cane crushing season. The shortage of sugarcane by-products such as bagasse and molasses during off-season is one of the major constraints of electricity and ethanol production in a sugar mill. Therefore, in recent years, the sugar industry has become interested in the use of supplemental feedstocks that would enable them to expand their operational season.

Among the feedstocks under study, special attention has been paid to the use of energy crops such as *Arundo donax*, energy cane (*Saccharum sponteneum*), *Eucalyptus camaldulensis*, gliricidia (*Gliricidia sepium*) and *Leucaena leucolephala* [4–6]. With the current technology available in the region, all the aforementioned crops can only be processed for electricity generation, except energy cane. Energy cane can be used for electricity and ethanol production.

It is well known that the land area available plays a critical role when it comes to energy production. Thus, it is important to focus on potential feedstocks available for conversion into multiple products. This is the case of sweet sorghum, which is considered a crop close to sugarcane and a viable alternative for ethanol production in some regions of the world [3]. Furthermore, sweet sorghum can be grown as a supplementary crop to sugarcane and processed using the existing machinery of sugar mills [7–9].

In Panamá, several projects have been carried out by the National Secretary of Science and Technology (SENACYT) to produce ethanol from sweet sorghum. SENACYT reported that higher yields can be obtained from sweet sorghum compared with sugarcane in a year cycle, yields up to 90 t_{stems}[1]/ha[2] and 17 000 l_{juice}/ha can be achieved for ethanol production [10,11]. Besides these attractive characteristics, SENACYT states that the greatest advantage of sweet sorghum is its status as non-food crop [12]. Such status gives sorghum a competitive advantage over other feedstocks as the production of energy from food crops is related to sustainability problems [13,14].

Considering that Central America has the machinery, factories and experience with the use of this type of crop (sugar crop) in large-scale production, sweet sorghum could be an attractive bioenergy feedstock for the region.

This paper focuses on determining the potential for electricity and ethanol production from sweet sorghum in Central America. This work proposes the production of sweet sorghum on land under temporary agricultural crops, temporary meadows for pasture or fallow land. The land under permanent crops was not considered for this evaluation to prevent competition with food production. This study does not propose a competition between sweet sorghum and sugarcane. The primary aim is to use equipment that is not used for sugarcane during off-season. This analysis was based on the reality of each country to assess the potential benefits and disadvantages of using sweet sorghum as an energy crop.

2. Central America profile

In 2010, Central America reached a petroleum products import bill of USD$ 9 321 million (96 million barrels), which represented an increase of 24% with respect to 2009 [15]. Most of the fuel consumption in the area is related to the transportation sector, which consumes approximately 62% of all petroleum products in the region [15]. In order to show Central America's dependency on petroleum fuels, a selection of indicators are presented in Fig. 1.

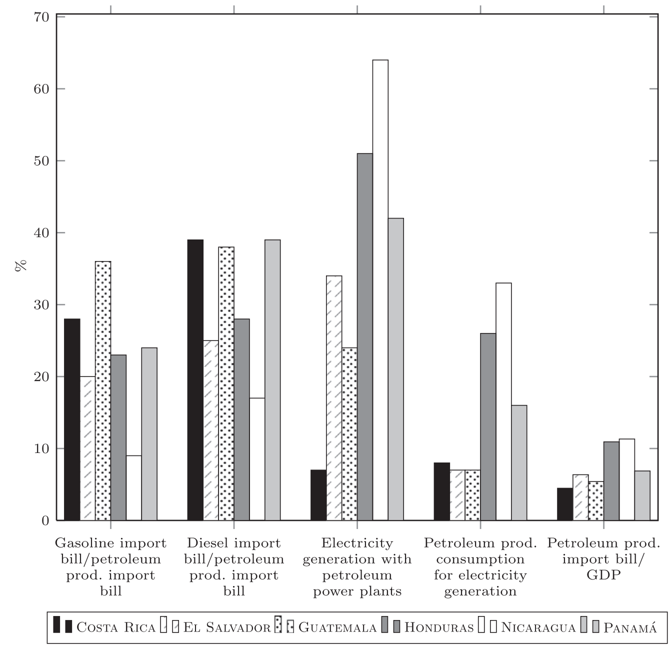

Fig. 1. Central America's dependency on petroleum products. Information was obtained from UN CEPAL SSeM [15,1].

With respect to gasoline and diesel consumption, the most vulnerable transportation sector in Central America belongs to Guatemala (Fig. 1). The gasoline and diesel imports of this country represent around 36% and 38% of petroleum products import bill, respectively. In contrast, Nicaragua is the less dependent on petroleum-based fuels for transportation purposes. This is due to the fact that the Nicaraguan motor vehicle fleet is the smallest in the Central American region [16].

The other major use of fuels in Central America is for electricity production. Honduras and Nicaragua show heavy dependence on petroleum fuels for electricity generation, more than 50% of their energy is produced by petroleum power plants. That is, plants that usually use fuel oil or a mixture of diesel fuel oil to generate electricity. At a regional level, Costa Rica seems to be in a better position, only 8% of petroleum derivatives are destined for electricity generation.

The petroleum products bill per unit of Gross Domestic Product (GDP) indicator shows the percentage of final goods and services produced that is used to pay petroleum products bills (Fig. 1). The countries that struggle more to pay bills are Honduras and Nicaragua, which spent around 10 and 11% of their GDP, respectively.

In order to have a healthy region with low dependence on petroleum-derived products, efforts have to be made to increase the use of renewable energy technologies and fuels. That is, encouraging electricity generation from renewable resources such as biomass and production of renewable fuels such as ethanol.

Currently, CHP plants in Central America have a total installed electricity capacity of 723.8 MW for a generation of 1 775.9 GWh [1]. Guatemala and Nicaragua account together for 68% of total installed capacity for a generation of 72% of regional production [1]. Most of the electricity production from CHP plants in Central America is provided by sugar mill cogeneration plants. However,

[1] Stems refers to the main body or stalk of a plant.
[2] ha: hectares.

Table 1
Potential feedstocks for energy production in a sugar mill CHP plant.

Feedstock	Growth cycle	LHV (MJ/kg)
Acacia mangium	6–7 years[a]	19.97[b]
Eucalyptus camaldulensis	5 years[c]	20.09[b]
Guazuma ulmifolia[b]	31 months[d]	18.51[b]
Gliricidia sepium[b]	1–3 years[e]	20.51[b]
Gmelina arborea[b]	5 years[f]	20.09[b]
Leucaena leucolephala[b]	2–5 years[g]	18.61[b]
Tectona grandis	4 years[h]	20.93[b]
Arundo donax	5 months[i]	15.07[i]
Gliricidia sepium	19 months[i]	20.53[j]
Cassia spectabilis	18 months[k]	–
Energy cane	10–15 months[l]	7.5[m]
Sweet sorghum	3.5 months[l]	7.6[n]

[a] Sein [55].
[b] FAO [54].
[c] Sajjakulnukit and Verapong [56].
[d] Centro Agronómico Tropical de Investigación y Enseñanza [57].
[e] Natural Resources Institute [58].
[f] Duke [59].
[g] Parrotta [60].
[h] Karmacharya and Singh [61].
[i] El Viejo [6].
[j] Parrotta [62].
[k] Staghl et al. [63].
[l] Misook Kim and Day [5].
[m] Bocci et al. [64]—sugarcane bagasse.
[n] Woods [26]—sweet sorghum bagasse (50% moisture).

this production is strongly limited by the length of the sugarcane crushing season.

As storing sugarcane bagasse to generate electricity during off-season is uneconomic, the CHP plant requires a secondary fuel such as fuel oil, coal, etc. For example, the San Antonio sugar mill (NSEL) in Nicaragua uses eucalyptus as fuel during the non-harvest season of May–July for a generation of about 17 MWh [17]. In Honduras, due to the high price of fuel oil, sugar mills are using coal (imported from Colombia) during the non-harvest season of May–November [18].

With respect to ethanol production, Guatemala is currently the strongest biofuels producer in Central America. According to the Inter-American Bank (IDB), Guatemala produces over 44% of Central America's sugarcane-based ethanol [19]. The majority of the ethanol produced in the region is exported abroad [19].

Although Central America has made several efforts to introduce an ethanol program, most of them have failed for reasons discussed later in this work. The Guatemalan Renewable Fuels Association reported that the Central American region would require the production of 365 million liters of ethanol to supply the E10 blend market [19]. This demand could be potentially satisfied by fewer than 25 processing plants [19]. Although this increase may seem large, according to a study made by Leal [20], all Central American countries could easily increase their plants' capacity and agricultural land to provide the ethanol required to implement an ethanol program.

3. Sweet sorghum

Few studies have been conducted to explore the use of supplemental feedstocks to extend sugar mills energy production season [5,7,4]. The studied feedstocks vary from fast-growing tree species to short rotation agricultural crops (sugar crops: energy cane and sweet sorghum) (Table 1).

Most of these feedstocks have being mainly studied for electricity production (forestry species). Despite the fact that these species do not require such a long time scale as conventional forestry, on average their growth cycle for energy production is longer than in agricultural crops (Table 1). On the other hand, energy cane and sweet sorghum stand out due to their potential for electricity and ethanol production. Moreover, both can be handled by the traditional sugar cane harvest and processing system [5]. Although the two sugar crops are interesting, note that the crop cycle of energy cane is longer than sweet sorghum's (Table 1), which consequently limits bioenergy production. Furthermore, based on a study made by Kim and Day [5], sweet sorghum produces more ethanol from juice than energy cane.

Sweet sorghum is considered a high biomass and sugar yielding gramineous crop, which contains approximately equal quantities of soluble (glucose and sucrose) and insoluble carbohydrates (cellulose and hemicelluloses) [21]. This crop has the ability to grow under a wide range of environmental conditions and it has also better tolerance to drought, flood, water logging, soil salinity, alkalinity and acidity toxicity [22,23,9].

As sugarcane is the reference crop to produce sugar and ethanol in Central America, Table 2 presents a comparison between sugarcane and sweet sorghum.

One of the most remarkable characteristics of sweet sorghum is its Radiation Use Efficiency (RUE[3]), with one of the highest intercepted RUE of any plant species [7]. This allows sweet sorghum to grow rapidly under optimal conditions compared with sugarcane. While sugarcane can only be harvested once a year, sweet sorghum has a 3.5 month crop cycle and can be harvested at most three times per year. Although, according to studies made by PRAJ Industries Ltd., higher yields can be obtained when sweet sorghum is harvested twice a year [24].

Unlike sugarcane, sweet sorghum has lower agronomic requirements (Table 2) and therefore, lower production costs. The cost of producing sweet sorghum is less than 1/2 production cost of sugarcane [25]. Also, as can be seen from Table 2, sweet sorghum has a low stalk production and yields of fermentable sugars during its first rotation, whereas in the second rotation, both parameters are higher than in cane.

Sweet sorghum produces by-products (bagasse and molasses) similar to those related to sugarcane. The fibrous residues obtained from the extraction process can be used in the same way as cane bagasse to produce electricity, process heat and power [26]. The molasses from the crystallization process can also be used to produce ethanol, which later on can be employed in specially designed lanterns and stoves. The ethanol produced from sugar crops as sweet sorghum can be used also in spark-ignition (SI) engines in its pure form or by blending with gasoline.

The results of studies conducted with sweet sorghum to evaluate its fermentation process, showed a sugar to ethanol conversion efficiency of more than 90% [27]. On a daily basis sweet sorghum can produce over 50% more ethanol [28], and is 32% cheaper to produce than sugarcane-based ethanol [29]. The ethanol produced from sorghum has also better properties: less sulphur content, high octane rating and it is more automobile friendly than sugarcane (up to 25% blending) [30]. The stillage from sweet sorghum after the extraction of juice has also a higher biological value than cane bagasse when used as forage to animals [31]. According to Almodares and Hadi [23], sweet sorghum has a ratio of energy output to fossil energy input comparatively higher to sugarcane, sugar beet, maize and wheat.

[3] RUE is defined as the ratio of the accumulated crop dry weight to the cumulative amount of intercepted solar radiation.

Table 2
Comparison between sugarcane and sweet sorghum.

Parameters	Unit	Sugarcane	Sweet sorghum
Radiation use efficiency[a]	g dry biomass/MJ	2	3.6
Harvesting cycle[b]	months	10–12	3.5
No. of cycle in a year[b]		1	2
Water requirement[c]		100%	65–70%
Fertilizer requirement[c]		100%	35–40%
Stalk production[c]	t/ha/cycle	65–80	42–55 for one cycle/year 84–110 for two cycles/year
Brix[b]	(% juice)	13–15	11–13
Fermentable sugar concentration in stalk[c]	%w/w	10.0–14.0	9.0–12.0
Yield of fermentable sugars[c]	t/ha/cycle	6.0–10.5	3.6–6.2 for one cycle/year 7.2–12.4 for two cycles/year
By-products		Bagasse Molasses	Bagasse Molasses
Co-products		Electricity Ethanol	Electricity Ethanol
Bagasse (50% w/w moisture)[c]	t/ha/cycle	19–24 (30% on cane weight)	10–14 for one cycle/year 20–28 for two cycles/year
Ethanol (100% basis) yield[c]	l/ha/cycle	3 400–6 000	2 020–3 500 for one cycle/year 4 000–7 000 for two cycles/year

[a] Woods [26].
[b] Misook Kim and Day [5].
[c] PRAJ [24].

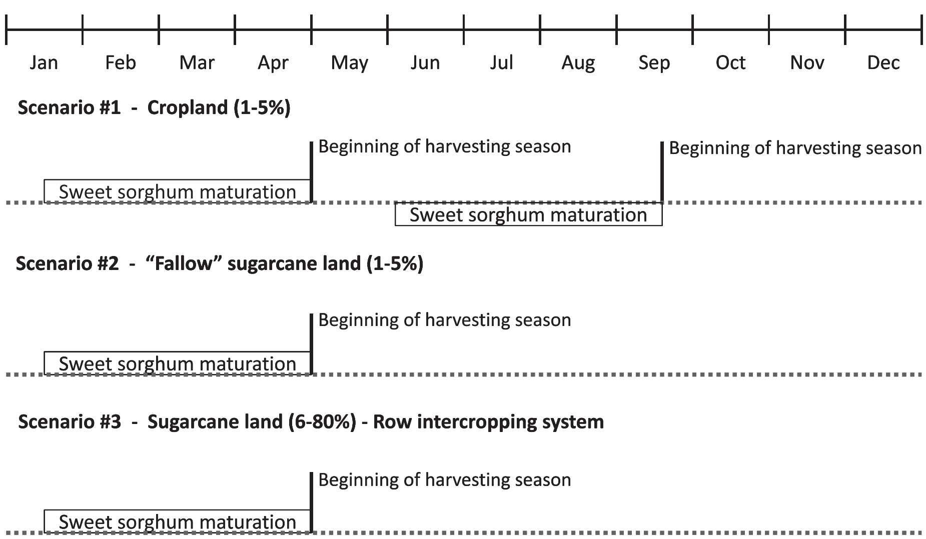

Fig. 2. Time scale and production scheme of the various scenarios.

4. Sweet sorghum potential in Central America

4.1. Material and methods

The percentage of land that may be suitable to be destined for sweet sorghum production has been varied in the following range: 1%–5% of cropland and 1%–80% of sugarcane land. For this purpose, three land availability scenarios are considered (Fig. 2). This study defines cropland as the areas under arable[4] and fallow land.[5]

For scenario #1, it is assumed that sweet sorghum can be grown on 1%–5% of cropland. For scenario #2, it is considered that sweet sorghum can be grown on 1%–5% of sugarcane land. These values represent the possible "fallow" sugarcane land available where sorghum can be grown and harvested before the start of the sugarcane harvesting season. For scenario #3, it is considered that sweet sorghum can be grown on 6% up to 80% of sugarcane land using a row intercropping[6] system. It is assumed a 1:1 row arrangement of sugarcane:sweet sorghum, where sugarcane is considered as the main crop and sweet sorghum as an intercrop. For this study's purposes, it is also considered that sweet sorghum can only be cultivated and harvested once a year. Data have been collected from FAO[7] to obtain the total area of cropland and sugarcane land in Central America.

As is shown in Fig. 3, Guatemala and Nicaragua are the countries with more area for planting and harvesting crops including sugarcane in the region. These lands account for 58% of the total cropland and sugarcane land in Central America. In addition, it is expected

[4] Arable land: land under temporary agricultural crops, temporary meadows for mowing or pasture, land under market and kitchen gardens and land temporarily fallow [52].

[5] Fallow land: cultivated land that is not seeded for one or more growing seasons [52].

[6] Row intercropping on sugarcane land: means growing sweet sorghum and sugarcane at the same time with at least one crop planted in rows.

[7] FAO: Food and Agriculture Organization of the United Nations.

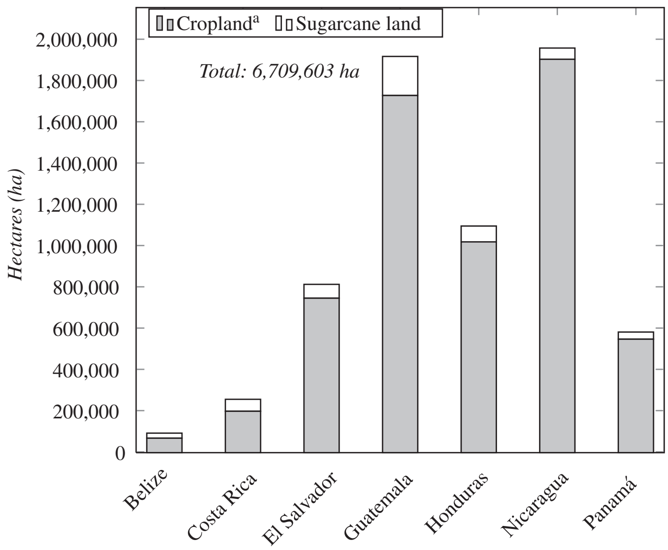

Fig. 3. Area harvested of cropland and sugarcane land. Data obtained from FAO [52]. [a] Includes only arable and fallow land.

Table 3
Proportional model to estimate the potential electricity and ethanol production from sweet sorghum.

Scenario	Electricity		Ethanol	
Scenario #1, #3	1.73Ac	MWhe[a]/ha	1.25Ac	kl EtOH[b]/ha
Scenario #2	3.46As	MWhe[a]/ha	2.5As	kl EtOH[b]/ha

[a] 1 MWhe = 1 000 000 Whe.
[b] 1 kl EtOH: 1 000 l of ethanol.

that for the coming years the area dedicated to sugarcane plantations in the region will increase significantly. For example, the Guatemalan Sugar Cane Producers Association (ASAZGUA) reported that for 2011–2012 harvest, Guatemala will increase the cultivated area of sugarcane from 223 000 to 248 000 ha [32]. Furthermore, ASAZGUA indicates that more land for sugarcane might become available in the south-western region toward the Mexican border, due to the fact that palm oil production is moving towards the Eastern and Northeastern part of the country [32]. The Guatemalan Sugarcane Research Center (CENGICAÑA) indicates that the total potential area that could be planted to sugarcane is 350 000 ha [32]. This value represents about 85% more than the sugarcane land considered for the Guatemalan scenario in the present work.

Plenty of land could also be available for sweet sorghum production in Nicaragua. Based on estimates made by the National Programme on Biofuels and Bioenergy, there is 1.2 million ha of fallow land in Nicaragua [33]. This value represents about 12% more than the maximum area of cropland considered for the Nicaraguan scenario.

In countries where the available useful land may become a limiting factor, the alternative relies on using sweet sorghum varieties with higher yields. Guigou et al. [34] indicates that many cultivars of sweet sorghum around the world can provide a diverse genetic base from which to develop regionally specific, highly productive cultivars.

Proposed model aims at assessing the potential of sweet sorghum as an energy crop in Central America. For this purpose, a proportional model was developed to estimate the potential electricity and ethanol production from sweet sorghum. The model is defined in terms of the type of land and area available to grow this energy crop.

Table 4
Electricity production of Central America's sugar mill CHP plants.

Sugar mills	Installed capacity[a] (MW)	Electricity generation[a] (MWh)	Energy sales[a] (MWh)	Total installed capacity (MW)	Total electricity generation (EG) (GWh)
Belize	–	–	–	–	–
Costa Rica				40	65.3
El Viejo	20	29 313.9	29 314		
Taboga	20	36 012.5	35 970		
Salvador				93.5	282.7
CASSA	50	174 362	–		
El Angel	22.5	71 455.1	–		
La Cabaña	21	36 917	–		
Guatemala			573 989	371.5	978.9
Madre Tierra	28	87 927.2			
Concepción	27.5	68 544.1			
La Unión	50	151 404			
Magdalena	131	316 562			
Pantaleón	55	181 026			
San Diego	21	39 685.9			
Santa Ana	40	122 506			
Tulula	19	11 262.7			
Honduras				88.3	142.1
AYSA	8	–	–		
Azunosa	4	11 000	11 000		
Cahsa	25.8	39 800	39 800		
Celsur	16.7	53 500	53 500		
Chumbagua	14	–	–		
La Grecia	12	17 100	17 100		
Tres Valles	7.8	20 700	20 700		
Nicaragua				121.8	306.9
Monte Rosa	62.5	111 080.7	114 050		
NSEL[b]	59.3	195 773	111 400		
Panamá	–	–	–	–	–

[a] UN [1].
[b] San Antonio sugar mill.

This model is constituted by two parameters: *Ac*, which represents the area of cropland and sugarcane land available to grow sweet sorghum under scenarios #1 and #3, respectively. *As* represents the area of sugarcane land available to grow sweet sorghum under scenario #2. The variables used to estimate the electricity and ethanol production are contained in a proportionality constant shown in Table 3. To estimate the electricity constant, it is assumed that yields of 46 t_{stems}/ha can be achieved for scenario #2, and yields of 23 t_{stems}/ha can be achievable for scenarios #1 and #3 [7]. It is considered a sorghum bagasse energy content of 7.6 GJ/t (50% moisture content, LHV[8]) and 186 kg bagasse (50% moisture) per t_{stems} [7]. To estimate the ethanol constant, it is assumed that yields of 2 500 l of ethanol/ha can be achieved for scenario #2, and yields of 1 250 l of ethanol/ha can be achievable for scenarios #1 and #3 [7].

To determine how significant could the electricity and ethanol production from sweet sorghum be for the processing plants in the region, data of Central American sugar mills cogeneration plants and distilleries have been collected. The data are presented in Tables 4 and 5.

As can be seen from Table 4, the biggest CHP plants are in Guatemala and Nicaragua. The Pantaleón and Monterosa sugar mills have an installed capacity of 62.5 and 55 MW, respectively. Currently, Guatemala is the largest CHP electricity producer in the region with 978.9 GWh.

[8] LHV: low heating value.

With respect to ethanol production, the biggest plants are in Costa Rica, Guatemala and Nicaragua (Table 5). The Taboga, Alcoholes MAG and San Antonio distilleries have an installed capacity of 300, 300 and 370 kl/day, respectively. Guatemala is the largest ethanol producer in the region with 203 000 kl per year.

Table 5
Ethanol production of Central America's distilleries.

Distilleries	Installed capacity (kl/day)	Operation days	Annual production estimate (kl)	Country installed capacity estimate (kl/day)	Country ethanol production estimate (ETP) (kl/year)
Belize	–	–	–	–	–
Costa Rica					
Taboga	300[a]	–	20 000[a]	540	48 800
CATSA	240[b]	120	28 800[c]		
El Salvador					
La Cabaña	120[d]	120	14 400[c]	120	14 400
Guatemala[e]					
Palo Gordo	120	150	18 000	990	203 000
Servicios Manufactureros	120	330	38 000		
Bioetanol	200	150	22 000		
DARSA	250	310	80 000		
Alcoholes MAG	300	150	45 000		
Honduras	–	–	–	–	–
Nicaragua					
San Antonio	370[f]	120	44 400[c]	670	80 400
Monte Rosa[g]	300[h]	120	36 000[c]		
Panamá	–	–	–	–	–

[a] Taboga sugar mill [65].
[b] Leal [20].
[c] To estimate the annual production it was assumed an operation period of 120 days.
[d] Asociación Azucarera de El Salvador [66].
[e] Tay [19].
[f] Nicaragua Sugar Estates Limited [17].
[g] The Pantaleón sugar Holding is planning to install in short term a distillery with these characteristics.
[h] Pantaleón sugar Holding [67].

4.2. Results and discussion

The results obtained for all scenarios considered in this study were analysed separately, i.e., growing sweet sorghum on cropland or sugarcane land. The best results can be obtained if the occurrence of scenarios is supposed to happen at the same time, i.e., growing sweet sorghum on cropland and sugarcane land. Under this scheme, the values for the production of electricity and ethanol of both scenarios should be added.

The results obtained for electricity production (SEP) and the percentage of electricity demand that could be theoretically supplied with sweet sorghum (SEP/ED) is presented in Fig. 4. These results were obtained by using the model for electricity production presented in Table 3 and data shown in Fig. 3. Unfortunately, data for electricity demand in Belize were not available for the period analyzed. Thus, the Belizean SEP/ED indicator could not be estimated.

As is shown in Fig. 4a, the Central America's top electricity consumers in 2008 were Costa Rica with 9 414 GWh and Guatemala with 8 646 GWh, accounting together for 45% of total electricity demand. This can be explained by the fact that these countries reported the highest GDP in the region for the period analyzed [35]. That is, families with greater income levels are more likely to spend their money in home appliances and governments with higher revenue usually invest more in improving electricity coverage.

In the left axis of Fig. 4a, SEP indicator is presented. The results show that by growing sweet sorghum on 5% of Central America's cropland, sorghum could supply about 536 GWh, which could represent around 10% of region's electricity demand. Note that under this scenario, Nicaragua could be the largest producer of sorghum-based electricity, providing about half of the region's production.

Under scenario #2 using 5% of sugarcane land, Central America could generate electricity between 17 and 87 GWh, providing between 0.25 and 1.26% of region's electricity demand. At a regional level, the country with the highest potential is Guatemala, where about 0.38% of the country's electricity demand could be supplied with sweet sorghum (Fig. 4b).

Under scenario #3 using 80% of sugarcane land, sweet sorghum could supply about 695 GWh, which could represent around 10% of Central America's electricity demand. The country with the highest potential under this scenario is Guatemala, about 3.01% of the

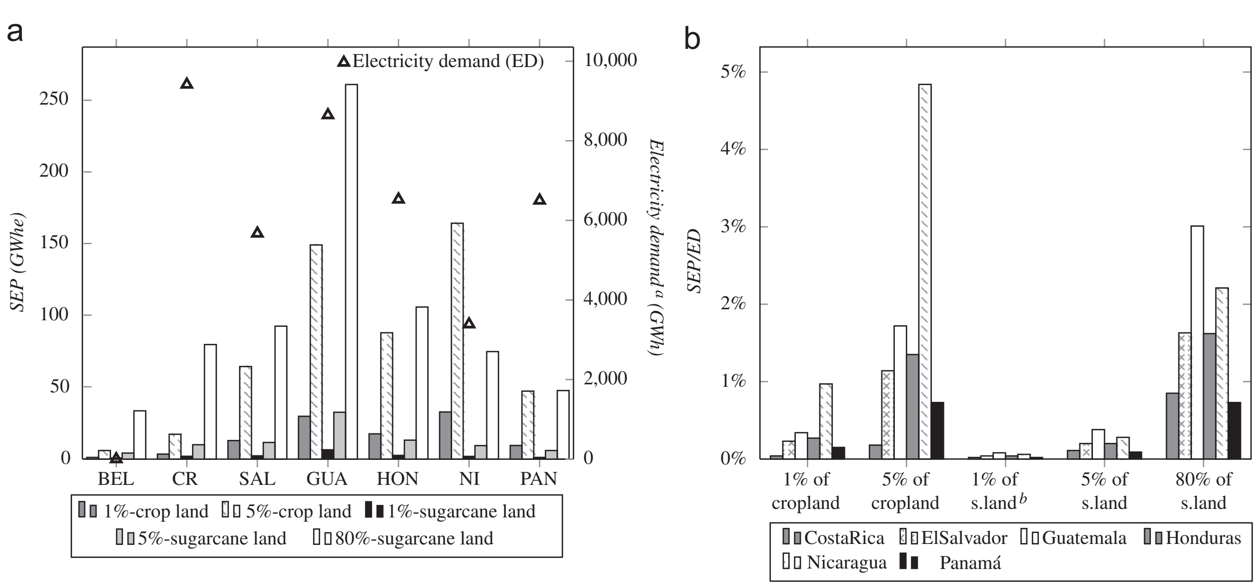

Fig. 4. Potential electricity production from sweet sorghum in Central America. (a) OLADE [53]. (b) Sugarcane land.

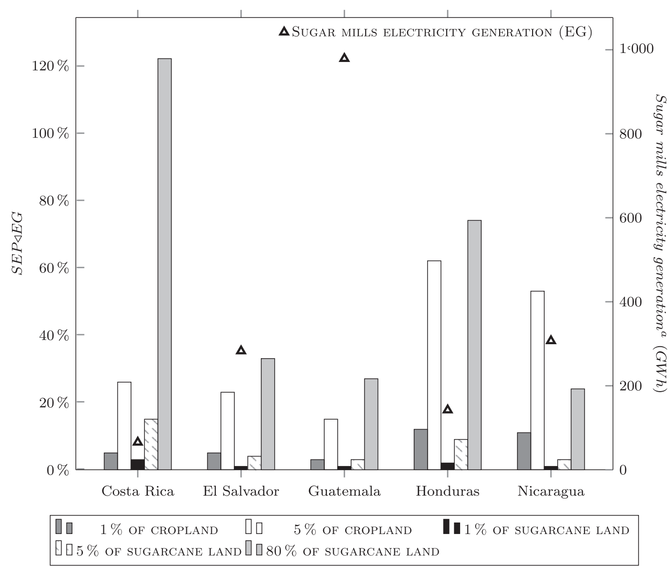

Fig. 5. Potential electricity production from sweet sorghum in Central America's sugar mill CHP plants. (a) Table 5; UN CEPAL SSeM [1].

country's electricity demand could be supplied with sorghum (Fig. 4b).

Once the potential sorghum-based electricity generation is estimated, it is necessary to determine how significant could this production be for sugar mill CHP plants. Thus, a new indicator is presented in Fig. 5 to show in which percentage the processing plants would have to increase their production to meet sorghum-based electricity demand (SEP/EG). This indicator was calculated assuming that the length of the cane and sorghum crushing season are the same (between 120 and 170 days). Summary results for the three scenarios are presented in Fig. 5.

As can be seen, all the bagasse-based CHP plants in Central America could easily process sweet sorghum to meet the production projections for all scenarios presented in Fig. 4a. Only plants in Costa Rica under scenario #3 using 80% of sugarcane land would not be able to meet demand. This is due to the fact that the sorghum-based electricity production potential under this scenario is higher than the production capacity of CHP plants. This can also be interpreted as if CHP plants in Costa Rica would require a sorghum crushing season longer than cane to meet production forecasts.

Note that the production of electricity from sorghum under such a long crushing season is not suitable due to sub-utilization of most of the CHP plants. Under scenario #1 using 5% of cropland, plants in Honduras and Nicaragua would need to operate at about 63% of their production capacity in order to meet projections.

Under scenario #3 using 80% of sugarcane land, plants in Guatemala would have to run at 75% of their capacity to meet sorghum-based electricity production target.

Therefore, in order to use full CHP capacity to meet electricity production forecasts under each scenario considered here, sweet sorghum crushing season must be reduced. Note that the results presented in Fig. 4a represent the maximum sorghum-based electricity production that could be generated under the assumptions considered in this work, but that does not mean that all CHP plants in Central America are ready for such production or are able to work efficiently under this scheme. Therefore, the land area necessary for sweet sorghum cultivation will strongly depend on the installed capacity of the CHP plants and length of the sorghum crushing season required to not interfere with sugar production.

To estimate the length of the crushing season required, it is assumed that CHP plants operate with a load factor of 60% under 24 h operation. For example, if the El Viejo and Taboga plants operate under these conditions, both plants would require a mean sorghum crushing season of 30 days to meet electricity production of scenario #1 using 5% of cropland. Under scenario #3 using 80% of sugarcane land, these plants would require a mean sorghum crushing season of 138 days for the production of 79.70 GWh. Such a long crushing season is not a feasible scenario due to problems related to the rainy season. The heavy rains in the region could limit the harvesting and transporting of sweet sorghum from the fields to the mill. Thus, in the case of Costa Rica, new CHP plants have to be built or the existing ones have to expand their installed capacity.

From these results (Figs. 4 and 5), it is seen that sweet sorghum implementation provides a good opportunity for the region to reduce its fossil fuel dependence for electricity generation. Under scenario #1 using 5% of cropland, Central America could increase its CHP share of electricity supply from 4.4% to 5.6%. This result is obtained by considering that no investments are made in Panamá to incorporate CHP plants. Otherwise, Central America could increase its CHP share of electricity supply up to 5.7%. Furthermore, countries such as El Salvador, Guatemala and Nicaragua could replace their petroleum-based electricity generation with sorghum-based electricity in 3%, 8% and 8%, respectively. The increase in renewable electricity production would allow Guatemala, Honduras and Nicaragua to reduce fossil fuel bills by USD$ 13, 10 and 20 million, respectively.

Under scenario #3 using 80% of sugarcane land, Central America could increase its CHP share of electricity supply from 4.4% to 5.9%. It is assumed that no investments are made in Panamá. Otherwise, Central America could increase its CHP share of electricity supply up to 6%. Furthermore, countries such as Costa Rica, El Salvador and Guatemala could replace their petroleum-based electricity generation with sorghum-based electricity in 12%, 5% and 14%, respectively. This approach would allow Costa Rica, Guatemala and Honduras to reduce fossil fuel bills by USD$ 15, 22 and 12 million, respectively.

On the other hand, as aforementioned, the integration of sweet sorghum into Central America's sugar mills would allow CHP plants to operate beyond the cane crushing season. This study proposes to process sweet sorghum, at least 1 month before, and 1 month after the sugarcane season. The successful implementation of scenarios that require a sorghum crushing season beyond 60 days to meet the production projections presented in Fig. 4 will strongly depend on the rainy season. Thus, if countries would like to reach these production levels, they would need to consider to increase the installed capacity of the existing plants or building new ones.

Under scenario #1 using 5% of cropland, the CHP plants in Costa Rica, El Salvador and Guatemala would require a mean sorghum crushing season of 30, 44 and 26 days, respectively, to meet sorghum-based electricity production forecasts. On the contrary, the Azunosa, Celsur, Tres Valles and San Antonio sugar mills would require a mean crushing season of 123 days. As this length of crushing season is not feasible, the Azunosa, Celsur, Tres Valles and San Antonio sugar mills would need to increase their installed capacity up to 8, 39, 15 and 121 MW, respectively, to have a crushing season below 60 days.

Under scenario #3 using 80% of sugarcane land, plants in El Salvador, Guatemala and Nicaragua would require a mean sorghum crushing season of 64, 46 and 43 days, respectively, to meet projections. On the other hand, sugar mills such as El Viejo, Taboga, Azunosa, Celsur and Tres Valles would require a mean crushing season of 144 days. As the length of this crushing season is over 60 days, these sugar mills would need to increase their installed capacity up to 41, 51, 10, 46 and 18 MW, respectively, to meet production forecasts.

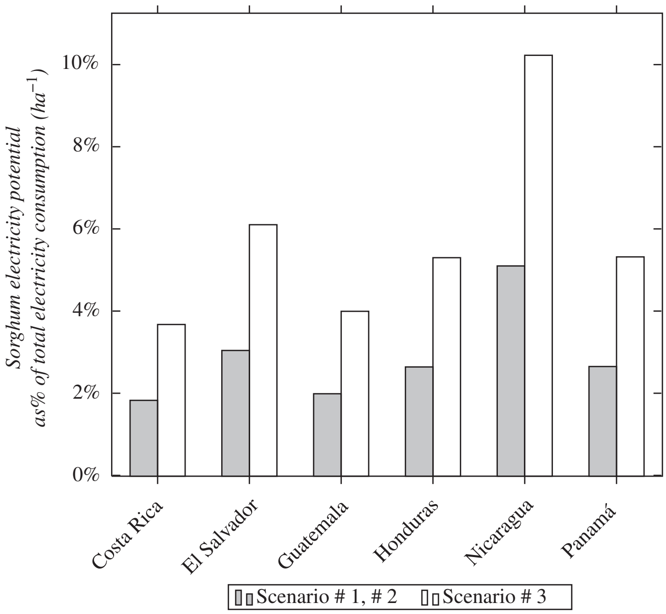

Fig. 6. Sorghum electricity potential as % of total electricity demand (% ha^{-1}).

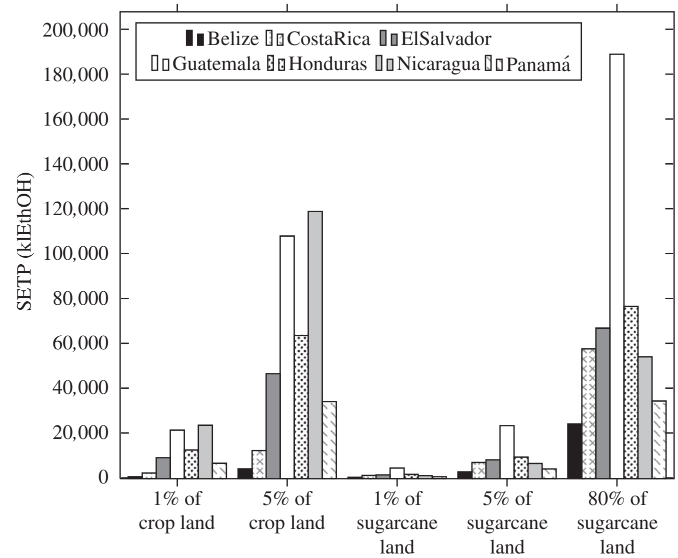

Fig. 7. Potential ethanol production from sweet sorghum in Central America.

Multiple scenarios can be developed in terms of the area available to estimate the percentage of electricity demand that could be supplied with sorghum (SEP/ED indicator). For this purpose, Fig. 6 can be used to assess sweet sorghum share in country's electricity demand for any given land area in the Central American region.

These values were calculated in terms of the proportionality constant showed in Table 3. To calculate the SEP/ED indicator, the land available for sweet sorghum must be multiplied by the percentage showed in Fig. 6. As can be seen, the greatest impact would be in El Salvador and Nicaragua due to their low levels of electricity demand (Fig. 4a). However, because El Salvador is one of the countries with less area of cropland and sugarcane land in Central America (Fig. 3), the electricity supplied by sorghum is less when compared with other countries.

For example, if sweet sorghum is grown on 3% of cropland and 40% of sugarcane land, the best results are obtained for Guatemala and Nicaragua. These countries could supply up to 2.5% and 4% of country's electricity demand, respectively (results based on Fig. 6). Under this scenario, both countries could increase CHP's share of national electricity production from 12.4% to 14.7% for Guatemala, and from 3.9% to 5.5% for Nicaragua. The same procedure can be followed to estimate the percentage of country's electricity demand that could be supplied by a sugar mill cogeneration plant. For example, for the year 2010, the area of sugarcane land of the Pantaleón (Guatemala) and El Angel (El Salvador) sugar mills was 52 377 ha [36] and 17 537 ha [37], respectively. Considering that both plants grow sweet sorghum in 80% of their sugarcane land. The Pantaleón and El Angel sugar mills could supply up to 0.84% and 0.43% of country's electricity demand, respectively.

With respect to ethanol production (SETP), the results obtained for all scenarios are presented in Fig. 7. These were calculated by using the model for ethanol production presented in Table 3 and data shown in Fig. 3.

The results show that by growing sweet sorghum on 5% of cropland, Central America could produce about 387 million liters of ethanol. Guatemala and Nicaragua would account together for 58% of regional production.

Under scenario #2 using 5% of sugarcane land, Central America could produce about 62 million liters of ethanol. Guatemala could be the largest sorghum-based ethanol producer in the region, providing about 38% of Central America's production.

Under scenario #3 using 80% of sugarcane land, Central America could produce about 502 million liters of ethanol. Guatemala and Honduras would account together for 53% of regional production.

In 2011, Canada (sixth position) and Australia (ninth position) were between the world's top 10 ethanol fuel producers, with a production around 462.3 and 87.2 million of U.S. liquid gallons, respectively [38,39]. Based on these productions and on the results presented in Fig. 7, it can be seen that sweet sorghum would allow Central America to have a strong biofuel industry no only in the continent, but in the world.

To determine how significant could these production forecasts be for Central American distilleries, SETP/ETP indicator was calculated. This indicator shows the percentage in which distilleries would have to increase their production, if the level of cane-based ethanol exports and ethanol demand for industrial use are kept constant. To determine the length of the operation period required, it is assumed that distilleries operate in their full capacity under 24 h operation. The results obtained for SETP/ETP indicator are presented in Table 6.

Table 6 shows that under scenario #1 using 5% of cropland, only ethanol plants in Costa Rica could easily increase their production to meet sorghum-based ethanol production forecasts. The Taboga and CATSA plants would require to increase their operation period in 17 and 31 days, respectively. On the other hand, processing plants in El Salvador and Nicaragua would not be able to produce sufficient ethanol to meet production projections.

Under scenario #2 using 5% of sugarcane land, all Central American distilleries could easily increase their production to meet sorghum-based ethanol demand.

Under scenario #3 using 80% of sugarcane land, all distilleries in the region would need to increase significantly their production and in some cases, some would be unable to meet production forecasts. The best results are obtained for the Taboga and Nicaragua's distilleries. These plants would need to increase their current production in 79 and 81 days, respectively, to meet sorghum-based ethanol production needs.

Although the increase in the operation period or installed capacity may seem large, Central America is currently working towards increasing installed capacity of distilleries to keep up with the ethanol demand of the international markets. According to a study made by Tay [19], Guatemala has an ethanol production

Table 6
Potential ethanol production from sweet sorghum in Central America's distilleries.

Distilleries	SETP/ETP 1% of cropland (%)	OD[a]	SETP/ETP 5% of cropland (%)	OD	SETP/ETP 1% of s. land[b] (%)	OD	SETP/ETP 5% of s. land (%)	OD	SETP/ETP 80% of s. land (%)	OD
Belize	–	–	–	–	–	–	–	–	–	–
Costa Rica	5		26		3		15		118	
Taboga		3		17		2		10		79
CATSA		5		31		4		18		142
El Salvador	65		324		12		58		465	
La cabaña		78		389		14		70		558
Guatemala	11		53		2		12		93	
Palo Gordo		16		80		3		17		139
Servicios Manufactureros		34		168		7		37		294
Bioetanol		12		58		3		13		102
DARSA		34		170		7		37		297
Alcoholes MAG		16		80		3		17		139
Honduras	–	–	–	–	–	–	–	–	–	–
Nicaragua	30		148		2		8		67	
San Antonio		35		177		2		10		81
Monte Rosa		35		177		2		10		81
Panamá	–	–	–	–	–	–	–	–	–	–

[a] Operation days.
[b] Sugarcane land.

potential of 520 million liters by 2015. This value represents about 256% more than the production capacity considered for the Guatemala scenario in the present study. Under a 520 million liters capacity, Guatemala's distilleries would need to increase their production up to a maximum of 36% of their capacity to meet ethanol production projections of all scenarios considered in this work.

As aforementioned, ethanol produced from sugar crops can be used as fuel in any petrol powered engine. Therefore, based on production projections presented in Fig. 7 and data about fuel consumption [15], the sorghum-based ethanol necessary to launch an ethanol program in Central America is estimated. This calculation is made by assuming that the level of cane-based ethanol exports and ethanol demand for industrial use keep constant. That is, only ethanol produced from sweet sorghum is used to supply the local market. It is also considered that all ethanol production under the proposed scenarios is used to supply ethanol–gasoline blends or ethanol–diesel blends, nor both.

The ethanol required and percentage of ethanol demand that could be supplied with sorghum to meet ethanol–gasoline and ethanol–diesel fuel blends is shown in Tables 7 and 8. With respect to ethanol–gasoline blends, the "E" designates ethanol and the number next to E designates the volume percentage of ethanol. For example, the E5 means that 5% ethanol (99.9% purity) was blended with 95% gasoline by volume. As for ethanol–diesel fuel blends, the "ED" designates ethanol and the number next to ED designates the volume percentage of ethanol. For example, the ED5 means that 5% ethanol was blended with 95% diesel by volume.

With respect to ethanol–gasoline blends, it can be seen from Table 7 that the countries with the largest ethanol demand are Costa Rica and Guatemala. This can be explained by the fact that these countries report the highest fuel consumption in the region. For example, in order to supply ethanol for blending E5, Costa Rica and Guatemala would require 48 and 65 million liters of ethanol, respectively.

Under scenario #1 using 5% of Central America's cropland, it was shown in Fig. 7 that sweet sorghum could produce around 387 938 kl of ethanol. Also, it can be seen from Table 7 that the ethanol demand to implement an E3 or E5 program in the region is around 140 and 234 million liters of ethanol. Therefore, sweet sorghum could provide 276% and 166% more ethanol than the necessary for blending E3 and E5 blends, respectively. Assuming an average price of gasoline of USD$ 5.05 per gallon, sorghum-based ethanol would help Central America to reduce fossil fuel bills by USD$ 517 million. Under this scenario, only Nicaragua could supply the ethanol required for up to E20 blends.

Under scenario #2 using 5% of sugarcane land, the Central American region would not be able to meet ethanol demand for any given blend using sweet sorghum. Although, Guatemala and Nicaragua could provide around 64% and 81% of ethanol demand, respectively, to implement an E3 program.

Under scenario #3 using 80% of Central America's sugarcane land, sweet sorghum could provide 358% and 215% more ethanol than the necessary for blending E3 and E5 blends, respectively. Such ethanol production would help Central America to reduce fossil fuel bills by USD$ 670 million.

From results in Table 7, it can be seen that all Central American countries would be able to supply the ethanol required to implement and maintain an E3 program (scenario #1). With the current installed capacity and keeping exports constant, any blend above E3 it is not a feasible scenario unless investments are made to either increase the operation period, installed capacity or build new plants. For instance, based on the current capacity of Central American distilleries (Table 5), if the Central American region would like to supply the ethanol required to reach E5 blends, distilleries in Costa Rica, Guatemala and Nicaragua would need to increase their operation in about 90, 66 and 22 days (average), respectively. Under this scenario, Guatemala and Nicaragua could supply ethanol fuel to Panamá and Honduras for blending E5.

The 100% ethanol option is far from Central American reality due to the fact that it would require a renewal of the current fleet and the introduction of Flex-Fuel vehicles. Besides the savings on fossil fuel bills that this project could deliver, this technology would allow the consumers to react to price signals and easily change from one fuel to the other on a daily basis.

With respect to ethanol-diesel blends (Table 8), Costa Rica and Guatemala would require 57 and 80 million liters of ethanol for reaching an ED5, respectively.

Table 7
Sweet sorghum ethanol as % of ethanol demand to use ethanol-gasoline blends.

	Belize	Costa Rica	El Salvador	Guatemala	Honduras	Nicaragua	Panamá
Gasoline							
Imports[a] (Mbbl)	–	5 258	2 862	8 586	4 105	707	4583
Consumption[a] (Mbbl)	–	6 095	3 699	8 181	4 565	1 866	5048
Imp/cons[a] (%)	–	86	77	105	90	38	91
Ethanol required for E3 blends (Ml)	–	29	18	39	22	9	24
Ethanol required for E5 blends (Ml)	–	48	29	65	36	15	40
Ethanol required for E10 blends (Ml)	–	97	59	130	73	30	80
Ethanol required for E20 blends (Ml)	–	194	118	260	145	59	161
Gasoline–ethanol blends				1% of cropland			
E3 (%)	–	9.16	56.38	58.91	62.31	284.55	30.31
E5 (%)	–	5.49	33.83	35.35	37.39	170.73	18.19
E10 (%)	–	2.75	16.91	17.67	18.69	85.36	9.09
E20 (%)	–	1.37	8.46	8.84	9.35	42.68	4.55
100% ethanol	–	0.27	1.69	1.77	1.87	8.54	0.91
				5% of cropland			
E3 (%)	–	45.84	281.80	294.59	311.57	1 422.59	151.66
E5 (%)	–	27.50	169.08	176.75	186.94	853.55	90.99
E10 (%)	–	13.75	84.54	88.38	93.47	426.78	45.50
E20 (%)	–	6.88	42.27	44.19	46.74	213.39	22.75
100% ethanol	–	1.38	8.45	8.84	9.35	42.68	4.55
				1% of sugarcane land			
E3 (%)	–	5.29	10.11	12.88	9.37	16.21	3.82
E5 (%)	–	3.17	6.06	7.73	5.62	9.73	2.29
E10 (%)	–	1.59	3.03	3.86	2.81	4.86	1.15
E20 (%)	–	0.79	1.52	1.93	1.41	2.43	0.57
100% ethanol	–	0.16	0.30	0.39	0.28	0.49	0.11
				5% of sugarcane land			
E3 (%)	–	26.45	50.55	64.42	46.86	81.08	19.08
E5 (%)	–	15.87	30.33	38.65	28.12	48.65	11.45
E10 (%)	–	7.94	15.17	19.33	14.06	24.32	5.73
E20 (%)	–	3.97	7.58	9.66	7.03	12.16	2.86
100% ethanol	–	0.79	1.52	1.93	1.41	2.43	0.57
				80% of sugarcane land			
E3 (%)	–	211.48	404.32	515.29	374.95	648.46	152.74
E5 (%)	–	126.89	242.59	309.17	224.97	389.08	91.64
E10 (%)	–	63.44	121.30	154.59	112.48	194.54	45.82
E20 (%)	–	31.72	60.65	77.29	56.24	97.27	22.91
100% ethanol	–	6.34	12.13	15.46	11.25	19.45	4.58

[a] UN CEPAL SSeM [15].

Under scenario #1 using 5% of Central America's cropland, sweet sorghum could provide 227% and 136% more ethanol than the necessary for blending ED3 and ED5 blends, respectively. Assuming an average price of diesel of USD$ 4.52 per gallon, sorghum-based ethanol would help the region reduce fossil fuel bills by USD$ 463 million. Under this scenario, only Nicaragua could meet ethanol demand for up to ED15 blends.

Under scenario #2 using 5% of sugarcane land, the region would not be able to meet demand for any given blend using sweet sorghum. Only Guatemala could provide around 50% of ethanol demand to reach ED3 blends.

Under scenario #3 using 80% of Central America's sugarcane land, sweet sorghum could provide 294% and 176% more ethanol than the necessary to use ED3 and ED5 blends, respectively. This ethanol production would help the region to reduce fossil fuel bills by USD$ 600 million. Under this scenario, Guatemala and Nicaragua could supply the ethanol required for an ED10 blend.

As can be seen from results in Table 8, all Central American countries would be able to supply the ethanol required to reach ED3 blends (scenario #1), except Costa Rica. If sugarcane producers want to keep constant the level of ethanol exports and ethanol production for industrial use, some investments are necessary to supply the ethanol required for certain ethanol–diesel blends. For example, based on the current capacity of Central American distilleries (Table 5), in order to meet ED5 blends, distilleries in Costa Rica, Guatemala and Nicaragua would need to increase their operation period in about 100, 76 and 38 days (average), respectively. To meet the region's demand, Guatemala and Nicaragua could supply ethanol fuel to Panamá and Honduras for blending ED5.

5. Energy policy

Almost inevitably, fossil fuel prices will continue rising for the foreseeable future, and with them the prices of electricity and transportation. Therefore, Central American countries must define an energy policy towards reducing fossil fuel dependence.

With respect to electricity production, over the last years, the Central American governments have enacted and implemented a series of regulations and policies to promote renewable electricity generation. For example, the Fiscal Incentives Law for the promotion of renewable energy technologies approved in 2007 by the Salvadoran government. This mandate includes exemption from import tariffs for capital goods and income tax for 5 years [40]. In Honduras, the Decree 70 promotes the development of renewable

Table 8
Sweet sorghum ethanol as % of ethanol demand to use ethanol–diesel blends.

	Belize	Costa Rica	El Salvador	Guatemala	Honduras	Nicaragua	Panamá
Diesel							
Imports[a] (Mbbl)	–	6 776	3 597	9 011	5 087	1 386	7 249
Consumption[a] (Mbbl)	–	7 630	4 500	9 250	5 512	3 282	7858
Imp/cons[a] (%)	–	89	80	97	92	42	92
Electricity generation[a] (Mbbl)	–	1075	8	26	22	98	993
Final consumption[a] (Mbbl)	–	6 555	4 492	9 225	5 490	3 185	6 865
Ethanol required for ED3 blends (Ml)	–	31	21	44	26	15	33
Ethanol required for ED5 blends (Ml)	–	52	36	73	44	25	55
Ethanol required for ED10 blends (Ml)	–	104	71	147	87	51	109
Ethanol required for ED15 blends (Ml)	–	156	107	220	131	76	164
Diesel–ethanol blends				1% of cropland			
ED3 (%)	–	7.51	40.96	46.10	45.72	147.10	19.66
ED5 (%)	–	4.51	24.58	27.66	27.43	88.26	11.80
ED10 (%)	–	2.25	12.29	13.83	13.72	44.13	5.90
ED15 (%)	–	1.50	8.19	9.22	9.14	29.42	3.93
				5% of cropland			
ED3 (%)	–	37.60	204.75	230.51	228.60	735.40	98.40
ED5 (%)	–	22.56	122.85	138.31	137.16	441.24	59.04
ED10 (%)	–	11.28	61.43	69.15	68.58	220.62	29.52
ED15 (%)	–	7.52	40.95	46.10	45.72	147.08	19.68
				1% of sugarcane land			
ED3 (%)	–	4.34	7.34	10.08	6.88	8.38	2.48
ED5 (%)	–	2.60	4.41	6.05	4.13	5.03	1.49
ED10 (%)	–	1.30	2.20	3.02	2.06	2.51	0.74
ED15 (%)	–	0.87	1.47	2.02	1.38	1.68	0.50
				5% of sugarcane land			
ED3 (%)	–	21.70	36.73	50.41	34.38	41.92	12.38
ED5 (%)	–	13.02	22.04	30.24	20.63	25.15	7.43
ED10 (%)	–	6.51	11.02	15.12	10.31	12.57	3.71
ED15 (%)	–	4.34	7.35	10.08	6.88	8.38	2.48
				80% of sugarcane land			
ED3 (%)	–	173.51	293.78	403.21	275.09	335.22	99.10
ED5 (%)	–	104.10	176.27	241.93	165.06	201.13	59.46
ED10 (%)	–	52.05	88.13	120.96	82.53	100.57	29.73
ED15 (%)	–	34.70	58.76	80.64	55.02	67.04	19.82

[a] UN CEPAL SSeM [15].

energy power plants through sales tax and import duties exemption for all equipment through the construction phase [40].

As a result of these regional efforts, biomass currently provides a significant portion of the region's renewable energy portfolio through CHP plants (Fig. 5). However, thermal technology (thermal power stations) still plays an important role on electricity generation in Central America. The switch to renewable electricity generation can result in important socio-economic and environmental benefits compared to fossil fuels. Therefore, governments need to keep working to increase the amount of electricity generated from renewable resources. For example, the Central American governments should consider changing regulatory environment and restructuring of the energy matrix. This process should take into account increasing energy supply by building CHP plants and market support for renewable energy technologies. Regulation should also include requirements that utilities distribute a minimum share of electricity from sweet sorghum (quota system). The creation of green power certificate programs for plants that produce electricity from sorghum could also be a helpful tool to promote projects. This certificate can be sold providing extra revenue for the processing plant. As part of this restructuring process, electricity producers and distributors should also be pressured to inform the public about the source of the energy (i.e., sugarcane bagasse, sweet sorghum bagasse or fossil fuels).

With respect to ethanol production, due to the absence of a domestic market for ethanol and biofuel law in Central America, most of the ethanol produced is exported overseas. For example, in Guatemala, most of the ethanol production is exported to Europe [19]. In El Salvador, all the ethanol produced is exported to the US market under the Central American-Dominican Republic Free Trade Agreement (CAFTA-DR) and to the Netherlands [41].

Although Central American countries have made several efforts to implement law and regulation for both biofuel and ethanol production, most of them have failed. There was an attempt to implement the Decree Law 17-85 known as “Law of the Carburant Alcohol” in Guatemala. However, the proposed law failed due to the lack of incentives for sugar producers and disagreements about the alcohol sales price to the refineries [19]. Furthermore, by the time this law was published, lead was substituted by MTBE, which was a less expensive gasoline additive than ethanol [19]. In 2003, the Guatemalan government created the Law of Incentives for the Development of Projects in Renewable Energy (DPRE), but as Decree 17-85, the law was never implemented.

Nowadays, only Costa Rica has made significant steps towards promoting law and regulation to reduce fossil fuel dependence. In 2004, the Costa Rican government released a “Petroleum Contingency Plan” to deal with sharp increases in oil prices. In 2008, based on the National Biofuel Program, Costa Rica established the mandatory use of gasoline-ethanol blends [42].

The rest of Central American countries is still evaluating the potential effects of implementing an ethanol-blending program. According to a report made by Herrera [41], the Salvadoran

government is working on legislation to promote sugarcane derived ethanol production, storage and sales. This law would mandate the implementation of an E5 blend.

In Guatemala, the Ministry of Energy and Mines (MEM) favours a gradual approach to implement an E10 blend, which would include a $1 per gallon subsidy to promote its production and consumption [19]. In contrast, the Guatemalan private sector proposes the use of 15% ethanol–gas mixtures, with a long-term final mix of 85% [19]. A report commissioned by the Organization of American States (OAS) to the firm Hart Energy proposes to start an ethanol program in 2012. The report recommends a progressive plan to use fuel ethanol blends of up to E10, and by 2014 start using biodiesel mixed in a ratio of up to 5% [43].

In Honduras, law and regulation for ethanol production has also been promoted. Such regulation includes incentives for businesses using at least 51% of the feedstock of Honduran origin [18]. Despite these efforts, the use of biodiesel and ethanol–gasoline blends in the country is almost negligible [44].

In Nicaragua, due to the lack of a legal framework to support the consumption of bio-fuels, the commercialization of ethanol domestically is also inhibited [45]. According to CEPAL [46], the Nicaraguan government is currently promoting a law to regulate the production and commercialization of biofuels. This energy policy will also include the sell of carbon credits under the Clean Development Mechanism (CMD).

Besides the need of a complete biofuel policy in Central America, some investments are also necessary to incorporate equipment and infrastructure (fuel pumps, subterranean deposits, etc.) for ethanol production and distribution. According to a study made by Horta [47], the implementation of an E10 program in the region would require a minimum storage capacity of 246 thousand m^3 for a crushing season of 100 days, and 153 thousand m^3 for a crushing season of 200 days.

According to a study made by Hart Energy [43], to implement and maintain an E10 program in Guatemala, it would be necessary an investment of USD$ 6 641 million over the 2011–2020 period. This value was calculated by considering that ethanol–gasoline blends are made in the distribution terminals. Over the implementation period, it is estimated that Guatemala would require a USD$ 25 million investment on infrastructure, transport and storage [43].

Despite the high investment costs required to launch an ethanol program, significant savings can be obtained from such implementation. For example, it is estimated that Brazil saved around USD$ 60 000 million in the 1970s with the introduction of fuel ethanol, either blended with gasoline, or used as hydrated ethanol in specially designed engines [48].

Besides the potential savings, the implementation of an ethanol program would also bring significant socio-economic benefits to the region. For example, the implementation of an E10 program in Central America would directly generate between 11 000 and 54 000 jobs, which represent about 0.18% and 0.86% of the PEA in rural areas, respectively [47]. In El Salvador, it is estimated that the implementation of an E5 program would create around 2 500 new jobs [41]. In Guatemala, the implementation of an E10 program would directly generate 5 000 jobs in harvesting and industrial processing [19].

Based on this information about the current status of ethanol production in Central America, it can be inferred that there is need for a strong political backing to launch an ethanol program (quantity-forcing policies). Therefore, as a first approach, each government should consider establishing a mandatory blend of ethanol in gasoline or diesel, with a small flexibility to float. This will prevent sugar mills to shift from sugar to ethanol production or vice versa depending on market prices. The shift in production can increase imbalance between supply and demand of fuel ethanol, leading to fuel scarcity.

On the other hand, the introduction of sweet sorghum into the Central American region may give rise to problems or difficulties related to the implementation process. One of the biggest challenges of sweet sorghum implementation could be to change Central America's conception related to the production of fuels from energy crops. The region's perception is largely negative towards this type of production. Potential issues can also come into view when dealing with difficulties in marginal land exploration, land tenure problems, public and private opposition, institutional cooperation and energy policy. For example, in the case of ethanol production, the serious problems with law enforcement in Central America has raised concerns in the fuel industry about misbranding[9] of ethanol fuel [19]. The oil industrialists and distributors believe that misbranding could affect the market competitiveness and cause economic losses related to product returns [19]. This sector also objects to the use of government subsidies and the large initial investments needed to develop a biofuels industry [19].

As an approach to these problems, the Central American governments must try to ensure a well-defined market control, regional taxes and set equal taxes for similar products. To avoid misbranding, governments must define clear specifications for fuels in order to assure the minimum content requirement of ethanol in fuel. With respect to land availability, a study made by CEPAL reported that the available land in Central America should be enough to produce biofuels in sufficient amounts to meet a 10% ethanol and 5% blend mandate [49]. They also recognized that new lands will have to be brought into production to achieve an ethanol program [49].

As can be seen, the development of law and regulation to promote the creation of sweet sorghum projects is a key tool to achieve sorghum implementation. According to Liao et al. [50] the countries that adopt more renewable energy (RE) policies appear to generate more RE products. Among those instruments, incentives/subsidies for production are decisive to the popularization of RE products. Therefore, to encourage the use of sweet sorghum for electricity and ethanol production, the Central American governments must create fiscal and economic incentives to attract potential investors. Such incentives could include: tax reductions to supply the local market, production subsidy for cultivating and producing RE products from sweet sorghum, and value-added tax exemptions for imported machinery and equipment. Note that this production subsidy must be strictly associated with the use of sweet sorghum for electricity or biofuel production and not associated with energy production per se. This is due to a subsidy related with the production of ethanol or electricity may involve the use of other resources. For example, the use of fossil fuels for electricity production. Furthermore, it is important that governments ensure the stability of the subsidy regime to avoid that potential investors rule out sweet sorghum projects.

As part of this incentive strategy, States could also provide loans for the purchase of equipment, materials, and services used for the design, construction, and installation of sweet sorghum projects. The use of the clean development mechanism (CDM) provides also a good opportunity for financing projects with greenhouse gas reduction. Thus, the Central American governments should consider to support public and private initiatives for the marketing of carbon credits from sorghum-based electricity production.

The Ministries or Secretaries of Agriculture and Livestock of each country also play an important role in sorghum implementation process. These entities should promote technical research and production of sweet sorghum for bioenergy purposes. Their role

[9] Misbranding: implies tax evasion and product adulteration.

should also include the development and implementation of a wide-ranging strategy to inform producers about the opportunities and benefits offered by sweet sorghum. According to a study made by Skoulou et al. [51], the use of energy crops could increase the farmers income and result in new job positions in rural areas. Agreements between producers and distributors are also a key component of the success of sweet sorghum projects.

6. Conclusions

The results obtained in this work show that sweet sorghum is a viable feedstock for bioenergy production in Central America. It is not expected that the use of sweet sorghum as an energy crop can fulfill region's energy needs. However, this study does highlight the potential of sweet sorghum to produce a clean and sustainable energy, using the same technology of Central American sugar mills.

The short growing period of sweet sorghum would allow CHP plants and distilleries to operate beyond the cane crushing season using sorghum by-products as raw materials. The electricity produced from sweet sorghum bagasse during off-season can be sold to the national grid. Meanwhile, the sorghum-based ethanol production can help to implement and maintain a sustainable ethanol program in the region. Sweet sorghum would allow to meet ethanol fuel demand, while keeping constant the cane-based ethanol exports and ethanol production for industrial use. This work proposes to process sweet sorghum 1 month before and 1 month after the sugarcane season.

The best scenario for bioenergy production is when sweet sorghum is grown on cropland (land under temporary agricultural crops, temporary meadows for pasture or fallow land). Under this scenario, sweet sorghum will not interfere with the growth, reproduction, and development of other species due to most of this land is marginal. Furthermore, farmers could obtain revenue from a short-rotation crop without restricting their ability to replant these fields to other crops.

The aforementioned scenario also provides the best results in terms of energy production (scenario #1%–5% of cropland). With respect to electricity generation, Guatemala and Nicaragua could supply around 1.72% and 4.84% of country's electricity demand, respectively. With respect to ethanol production, Guatemala and Nicaragua could easily supply ethanol for both E3 and ED3 blends. Moreover, Nicaragua has the potential to supply ethanol for up to E20 and ED10 blends. Note that the results for this scenario were obtained by assuming that sweet sorghum could only be harvested once a year. Thus, greatest results can be obtained for scenario #1 if sorghum is harvested two or three times per year.

Under scenario #2 (5% of "fallow" sugarcane land), Guatemala could supply up to 0.38% of country's electricity demand, using sorghum bagasse as raw material for electricity generation. With respect to ethanol production, the best results are obtained for Nicaragua, which could supply up to 83% of country's ethanol demand for blending E3.

The reality of the assumptions made for scenario #3 is open to debate but this analysis show that if sugarcane could be intercropped with sweet sorghum once a year, significant benefits can be achieved. Therefore, further research needs to be done in Central America to determine the effect of this system in sugarcane yields.

Unfortunately, due to the lack of relevant policies in Central America, the implementation of sweet sorghum could be jeopardized. The governments must define incentives and support mechanisms to encourage the use of sweet sorghum for bioenergy production. The promotion of national policies and laws can also catalyse the investments in sweet sorghum to meet targets in electricity and ethanol production.

On the other hand, although several sectors had criticized the production of energy from energy crops for posing a threat to food security, sweet sorghum will not affect food supply.

The approach for processing sweet sorghum in sugar mills aims at attaining a higher productivity, while sugarcane production is unaffected. The bet on energy plantations such as sweet sorghum can be an opportunity to promote the local agricultural industry, create employment, reduce greenhouse gas emissions and improve air quality. The additional growth of sweet sorghum outside the land owned by sugarcane companies would allow farmers to access the markets of the sugarcane agro-industry providing additional economic opportunities to rural communities. In terms of climate change values, the reduction of carbon emissions and creation of carbon credits to sell to the government can be a good alternative to contribute to the sustainable development of the region.

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